JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, F03016, doi:10.1029/2006JF000666, 2007

Sorted bed forms as self-organized patterns: 2. Complex forcing scenarios

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Received 23 August 2006; revised 6 March 2007; accepted 12 April 2007; published 14 August 2007.

[1] We employ a numerical model to study the development of sorted bed forms under a variety of hydrodynamic and sedimentary conditions. Results indicate that increased variability in wave height decreases the growth rate of the features and can potentially give rise to complicated, a priori unpredictable, behavior. This happens because the system responds to a change in wave characteristics by attempting to self-organize into a patterned seabed of different geometry and spacing. The new wavelength might not have enough time to emerge before a new change in wave characteristics occurs, leading to less regular seabed configurations. The new seabed configuration is also highly dependent on the preexisting morphology, which further limits the possibility of predicting future behavior. For the same reasons, variability in the mean current magnitude and direction slows down the growth of features and causes patterns to develop that differ from classical sorted bed forms. Spatial variability in grain size distribution and different types of net sediment aggradation/degradation can also result in the development of sorted bed forms characterized by a less regular shape. Numerical simulations qualitatively agree with observed geometry (spacing and height) of sorted bed forms. Also in agreement with observations is that at shallower depths, sorted bed forms are more likely to be affected by changes in the forcing conditions, which might also explain why, in shallow waters, sorted bed forms are described as ephemeral features. Finally, simulations indicate that the different sorted bed form shapes and patterns observed in the field might not necessarily be related to diverse physical mechanisms. Instead, variations in sorted bed form characteristics may result from variations in local hydrodynamic and/or sedimentary conditions.

Citation: Coco, G., A. B. Murray, M. O. Green, E. R. Thieler, and T. M. Hume (2007), Sorted bed forms as self-organized patterns: 2. Complex forcing scenarios, *J. Geophys. Res.*, *112*, F03016, doi:10.1029/2006JF000666.

1. Introduction

[2] Sorted bed forms or ''rippled scour depressions'' are sedimentary features characterized by slight topographic relief and asymmetric sequences of coarse sediment domains forming bathymetric lows and fine sediment domains forming bathymetric highs [*Cacchione et al.*, 1984]. These features are sometimes asymmetric in the sense that the coarse domains are actually centered on the updrift side of the bathymetric lows where they develop a sharp boundary with the fine sediment domain. The development of sorted bed forms on the inner continental shelf has recently been simulated using a simplified numerical model [*Murray and Thieler*, 2004] that produces a highly regular pattern displaying characteristics of spacing and relief that are similar to those observed worldwide (Table 1). Further developments of the numerical model [*Coco et al.*, 2007] have removed some of the assumptions present in the original model and introduced a description of physical processes based on widely accepted parameterizations.

[3] Larger wave-generated ripples develop over the coarse domains, increasing local turbulence and shear stress so that fine sediments are increasingly less likely to deposit on coarse domains. On the other hand, smaller wave-generated ripples develop over the fine domains, decreasing local turbulence and shear stress. As a result, fine sediments are increasingly more likely to deposit on fine domains. Migration of the sorted bed forms also allows coarse domains to incorporate other coarse material from the seabed, further reinforcing the pattern of sediment segregation into coarse and fine units. This embellished model still produces regular sorted bed form patterns that arise as a result of self-organization processes, primarily driven by interactions between the flow and the substrate, which becomes divided into coarse and fine domains.

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0148-0227/07/2006JF000666$09.00

Table 1. Characteristics of Inner Shelf Sorted Bed Forms[a]

Shape	Asymmetric	Spacing, m	Relief, m	Migration, m/yr	Depth, m	Grain Sizes, mm	Orientation	Waves	Currents[b]	Location	References
Linear	NA	60–100	NA	NA	0–20	$d_f \sim 0.2$, $d_c \sim 0.6$	shore normal	moderate	unidirectional	Cape Lookout (NC, USA)	*MacIntyre and Pilkey* [1969]
Linear	NA	irregular	0.5	NA	0–50	NA	shore normal	moderate to high	unidirectional	Balsa Delta (Mexico)	*Reimnitz et al.* [1976]
Linear	yes	10–100	1	NA	5–20	fine sand to gravel	shore oblique	moderate to high	unidirectional	Middle Atlantic Bight	*Swift and Freeland* [1978]
Linear	yes	NA	∼5	NA	>20	fine sand to gravel	shore parallel	NA	unidirectional	Middle Atlantic Bight	*Swift and Freeland* [1978]
V–shaped	yes	irregular	NA	NA	4–10	sand to gravel	shore normal	moderate to high	variable	Rhode Island (RI, USA)	*Morang and McMaster* [1980]
Linear	yes	irregular	1–3	NA	8<	$d_f = 0.35$, $d_c = 0.68$	shore normal	moderate to high	unidirectional	Cape Cod (MA, USA)	*Aubrey et al.* [1982]
V–shaped	yes	irregular	1–3	NA	8–18	NA	shore normal	moderate	unidirectional	Cape Cod (MA, USA)	*Aubrey et al.* [1982]
Patchy	NA	irregular	2<	NA	4–8	$d_f = 0.5–2$, $d_c = 2–8$	variable	high	variable	Nome Solomon (AK, USA)	*Hunter et al.* [1982]
Linear	NA	irregular	NA	NA	4–15	pebbly sand and gravel	fetch-parallel	high	variable	Port Clarence (AK, USA)	*Hunter et al.* [1982]
Linear/patchy	NA	irregular	5<	NA	30–90	fine sand to gravel	variable	moderate to high	bidirectional	Bristol Bay (AK, USA)	*Molnia et al.* [1983], *Schwab and Molnia* [1987]
Linear	no	irregular	1<	NA	30–65	$d_f = 0.25$, $d_c = 0.65$	shore normal	NA	NA	Central California (CA, USA)	*Cacchione et al.* [1984]
V-shaped	NA	200–400	1–2	NA	10–80	fine to coarse sand	variable	moderate to high	variable	Sydney (Australia)	*Field and Roy* [1984]
Linear	NA	irregular	NA	NA	15–65	polymodal sandy gravels	shore normal	moderate to high	NA	Nova Scotia (Canada)	*Forbes and Boyd* [1986]
Linear	no	100	∼1	variable	10–20	$d_f = 0.12–0.35$, $d_c = 0.35–1$	shore parallel	moderate to high	unidirectional	Monterey Bay (CA, USA)	*Hunter et al.* [1988], *Eittreim et al.* [2002]
Patchy	no	irregular	∼1	variable	20–60	$d_f = 0.12–0.35$, $d_c = 0.35–1$	variable	moderate to high	unidirectional	Monterey Bay (CA, USA)	*Hunter et al.* [1988], *Eittreim et al.* [2002]
Patchy	NA	irregular	NA	NA	6–8	$d_f = 0.2$, $d_c \sim 1$	variable	low to moderate	variable	Whangarei (New Zealand)	*Black and Healy* [1988]
Linear	NA	7–100	NA	NA	∼5	medium sand to gravel	shore oblique	high	variable	Beaufort Sea (Canada)	*Hequette and Hill* [1995]
Linear	yes	40–100	1<	yes	3–10	$d_f = 0.22$, $d_c = 2$	shore normal	moderate	unidirectional	Wrightsville (NC, USA)	*Thieler et al.* [1995, 2001]
Linear	yes	irregular	0.5–0.75	yes	10–20	$d_f = 0.22$, $d_c = 2$	shore oblique	moderate	unidirectional	Wrightsville (NC, USA)	*Thieler et al.* [1995, 2001]
Linear	NA	irregular	1–3	NA	50–75	fine to coarse sand	variable	moderate to high	variable	Farallon Islands (CA, USA)	*Chin et al.* [1997]
Patchy	no	irregular	1<	0–170	NA	medium to coarse sand	variable	moderate	variable	Folly Island (SC, USA)	*Thieler et al.* [1999]
Linear	yes	300–400	0.5–1	NA	>25	fine to coarse sand	shore normal	low to moderate	variable	Cape Rodney (New Zealand)	*Hume et al.* [2000]
Patchy	no	NA	0.5–1	NA	∼25	fine to coarse sand	shore normal	low to moderate	variable	Cape Rodney (New Zealand)	*Hume et al.* [2000]
Linear	NA	irregular	<1	NA	∼8–20	$d_f \sim 0.25$, $d_c > 0.5$	shore oblique	moderate	unidirectional	Long Island (NY, USA)	*Schwab et al.* [2000]
Linear	NA	5–25	0.5<	ephemeral	6–16	$d_f = 0.1$, $d_c = 1$	shore normal	moderate to high	NA	Tairua (New Zealand)	*Hume et al.* [2003]

Table 1. (continued)

Shape	Asymmetric	Spacing, m	Relief, m	Migration, m/yr	Depth, m	Grain Sizes, mm	Orientation	Waves	Currents[b]	Location	References
Linear	no	irregular	0.4–0.5	small	18–26	$d_f = 0.6$, $d_c = 2$	shore parallel	moderate to high	NA	Pauanui (New Zealand)	*Hume et al.* [2003]
Linear	no	250–500	NA	small	>30	$d_f = 0.6$, $d_c = 2$	shore oblique	moderate to high	NA	Tairua (New Zealand)	*Hume et al.* [2003]
Linear/patchy	NA	irregular	~1	ephemeral	3–9	$d_f = 0.25$, $d_c \gtrsim 2$	variable	low to moderate	bidirectional	West Florida (USA)	*Harrison et al.* [2003], *Donahue et al.* [2003]
Linear	yes	500–1000	<1	25–75	10–16	$d_f = 0.16$, $d_c =$ coarse	shore oblique	high	bidirectional	Grays Harbor (WS, USA)	*Ferrini and Flood* [2005]
Patchy	yes	500–1000	0.5–>1	ephemeral	8–16	NA	variable	high	NA	Eel River (CA, USA)	*Ferrini and Flood* [2005]
Linear	yes	100–150	<1	stable	16–36	NA	shore normal	high	NA	Eel River (CA, USA)	*Ferrini and Flood* [2005]
Linear	yes	100–150	<1	stable	16–36	NA	shore normal	high	NA	Eel River (CA, USA)	*Ferrini and Flood* [2005]
Linear	yes	irregular	~0.1– ~3	variable	8–18	$d_f \sim 0.25$, $d_c 0.\sim 75$	shore normal	moderate	variable	Martha's Vineyard (MA, USA)	*Goff et al.* [2005]
Linear/patchy	no	irregular	NA	no	26–37	$d_f \sim 0.16$, $d_c = 2.3$	shore oblique	high	bidirectional	German Bight	*Diesing et al.* [2006]

[a]NA indicates not available.
[b]The term "unidirectional" is used to indicate a dominant current direction.

[4] Whereas the companion paper [*Coco et al.*, 2007] focuses on developing the numerical model and testing its sensitivity to externally imposed conditions (wave height, current speed, sediment size) and internal parameterization of physical processes (vertical velocity and sediment concentration profiles, wave-generated ripple predictors), this study explores the patterns produced by the model and, at least qualitatively, compares these patterns with available observations. We will explain how variability in the morphology of the features can arise, which has also implications for the kinds of field observations that are now required to provide quantitative tests of the model's predictive ability.

2. Field Observations

[5] Recent detailed observations made off the USA [*Goff et al.*, 2005; *Ferrini and Flood*, 2005] and New Zealand coasts [*Hume et al.*, 2003; *Green et al.*, 2004] document complicated morphology and behavior of sorted bed forms with topographic reliefs varying over an order of magnitude (from 0.1 to 3 m) and a range of cross-sectional shapes (moats, steps, and dunes) and plan view patterns. Table 1 shows a summary of observations from the literature; sorted bed forms are not rare, and they occur under a variety of conditions. Overall, three types of shapes can be recognized: linear, patchy and offshore widening, indicated as V shaped in Table 1. Only in a limited number of cases can the bed form pattern be described as regular. Sorted bed forms at most sites display a grain size asymmetry with the coarse sediment domain present on the upcurrent side of the features. In particular, *Goff et al.* [2005] noted the presence of changes in the orientation of the cross-sectional asymmetry, the development of moat-like shapes inside the coarse sediment domains, and that the largest bed form reliefs could be associated with dune-like shapes and greatest contrast in grain size. In contrast to the observations off North Carolina [*Thieler et al.*, 1995, 2001; *Murray and Thieler*, 2004] and other locations, where the coarse domains extend from bathymetric troughs to the crests, some of the coarse domains off Massachusetts center on the bathymetric lows. Coarse domains are typically sharp edged in all locations. *Ferrini and Flood* [2005] reported observations from a number of locations and classified sorted bed forms (or "rippled scour depressions" in their notation) into three types. The first is shore normal, low amplitude, and affected by transverse flow although the wave-generated ripple orientation reflects the direction of propagation of surface gravity waves. For the observations described by *Ferrini and Flood* [2005], its dynamics can be linked to preexisting large-scale bathymetric patterns. The second type refers to larger features that extend further in both the alongshore and the cross-shore directions and that are characterized by a diffuse downdrift edge. The third type has been observed at shallower depths and is highly irregular, probably because of more complicated hydrodynamic patterns.

[6] Most authors (Table 1) indicate a large difference in mean sediment size for the coarse and fine domains

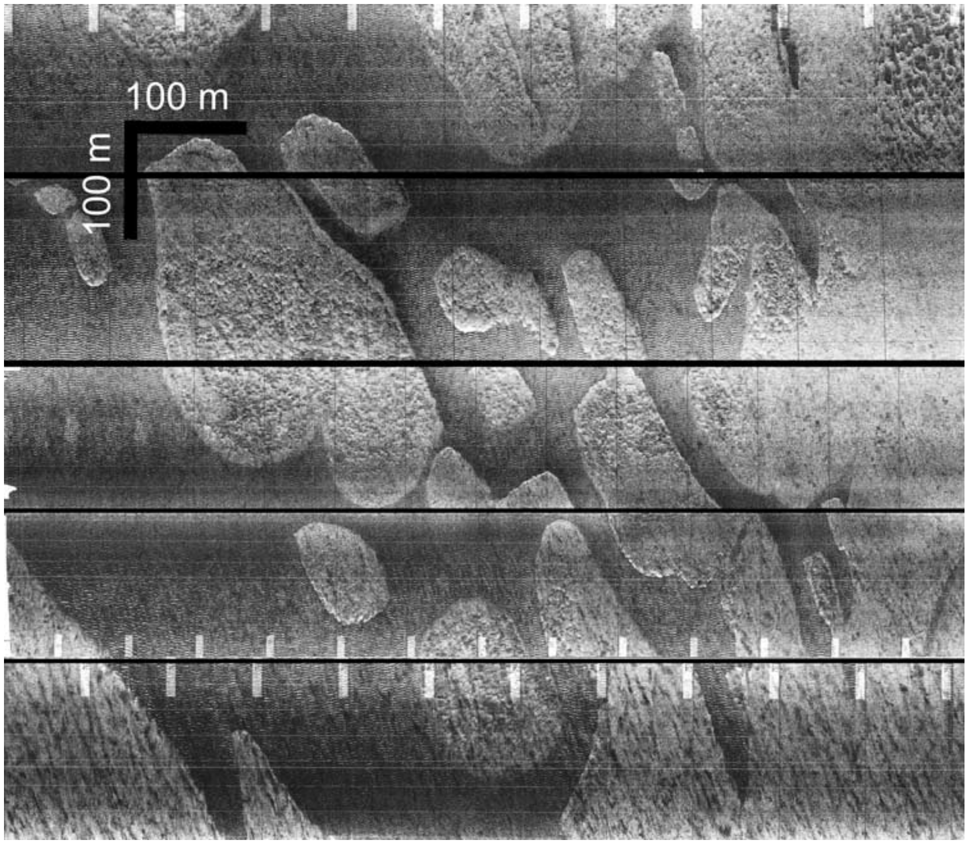


Figure 1. Side scan map of irregular field of sorted bed forms offshore of Cape Rodney, New Zealand. The features develop in around 35 m water depth. White (black) indicates fine (coarse) sediment. Horizontal black lines are the effect of boat tracks during the survey.

that, in some cases, reaches an order of magnitude [*Green et al.*, 2004; *Gutierrez et al.*, 2005; *Diesing et al.*, 2006]. *Goff et al.* [2005] shows that inside each domain the sediment distribution is unimodal and well sorted, implying a bimodal separation between fine and coarse domains. Most authors also indicate that medium sand appears to be absent and that the two sediment sizes are mixed only at the transition between fine and coarse domains.

[7] In terms of temporal evolution, *Hume et al.* [2003] report negligible migration of sorted bed forms apart from small back-and-forth migrations at the edges of the coarse and fine domains. Side scan observations described by *Goff et al.* [2005] showed changes up to 50 m over two years. Irregular migration patterns have also been reported (Table 1) with no net movement over part of the sorted bed form pattern, and expansion, contraction and translation over other parts [*Thieler et al.*, 1999; *Hunter et al.*, 1988]. Also, the direction of migration might not necessarily correspond to the grain size asymmetry of the features [*Goff et al.*, 2005]. Similarly, *Ferrini and Flood* [2005] report migration rates as high as 50 to 150 m in 2 years for the shore-normal type of bed forms characterized by an evident rhythmicity and a spacing between 100 and 150 m. Sorted bed forms off North Carolina exhibit slow migration in the direction suggested by their asymmetry [*Murray and Thieler*, 2004].

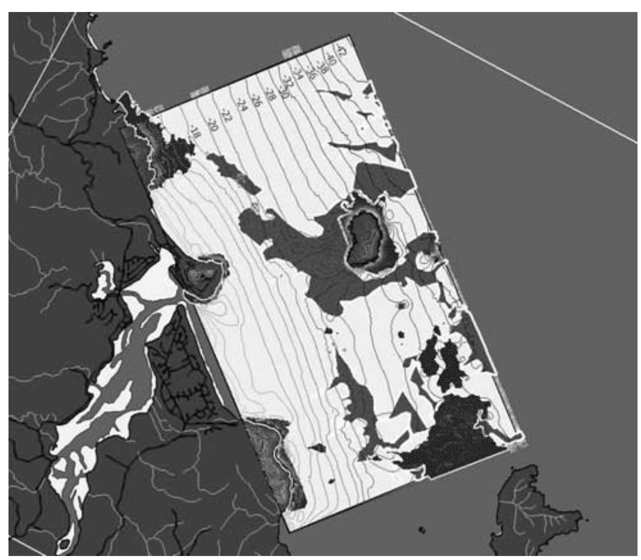


Figure 2. Side scan map of irregular field of large-scale sorted bed forms offshore of Tairua, New Zealand. The highly irregular features develop between 20 and 40 m water depth. The more regular and ephemeral sorted bed forms presented in Figure 1 of *Coco et al.* [2007] develop in shallower areas (water depths below 16 m) and were not present at the time of this survey. White (gray) indicates fine (coarse) sediment. Darker shades of gray indicate areas (including offshore islands) above mean water level.

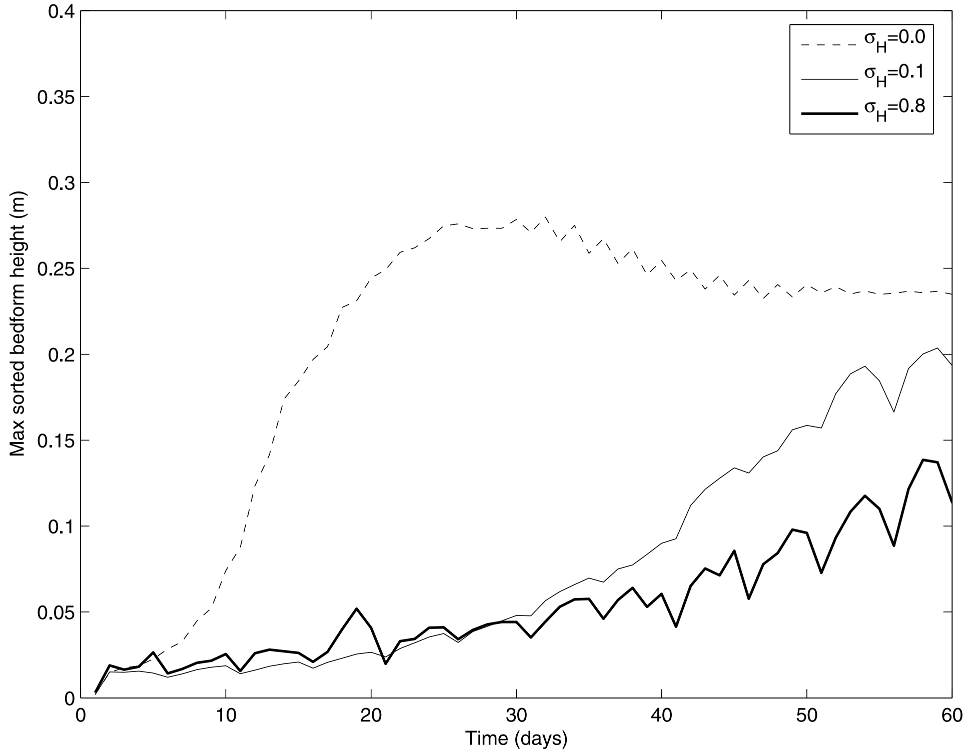


Figure 3. Growth rate of sorted bed forms over time. Mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Mean wave height is equal to 3 m, while the values of σ_H in the legend indicate the standard deviation around the mean wave height in the Gaussian distribution. Sorted bed form height is evaluated as the difference between the maximum and minimum bed elevation over the whole domain.

[8] With respect to the persistence of sorted bed forms, available observations (Table 1) seem to indicate that water depth is one of the primary controlling factors. In water depths less than 10–15 m sorted bed forms appear as ephemeral features [*Hume et al.*, 2003; *Ferrini and Flood*, 2005] that appear/disappear on timescales of the order of a few months although this could be an upper limit, dictated by frequency of surveys rather than by sorted bed form dynamics. In water depths greater than 15–20 m sorted bed form sometimes appear as stable features with limited changes over annual [*Hume et al.*, 2003; *Goff et al.*, 2005] or even decadal timescales [*Diesing et al.*, 2006].

[9] Despite the increasing number of observations, no study so far has assimilated all of the observations or, in particular, attempted to develop empirical predictors for spacing and amplitude of the features as a function of environmental variables such as water depth, sediment sizes, wave height or period, and magnitude of the mean current. Partly this is a result of the large variability in the geometry of the features, which, in many cases, do not even display a clearly rhythmic pattern (Table 1). It appears that sorted bed forms characterized by limited rhythmicity are more likely to occur at locations where hydrodynamics are complicated by the superimposition of wave-driven, tidal, and larger-scale currents (Table 1). For example, Figures 1 and 2 show irregular patches of sorted bed forms developing on the inner shelf of New Zealand at locations where currents are unlikely to be unidirectional [*Hume et al.*, 2000].

[10] Our model [*Coco et al.*, 2007] provides a possible unifying theory for the genesis and evolution of the features, and the simulations to be presented herein explain how variability in morphology can arise from spatial variability in sediment composition and temporal variability in forcing. With a better understanding of how variability can arise, we are better able to state what is now required to provide quantitative tests of the model's predictive ability.

3. Model Parameterization

[11] The reader is referred to the companion paper [*Coco et al.*, 2007] for a detailed description of the numerical model. We consider two sediment sizes: the fine fraction, characterized by d_{fine} = 0.15 mm, and the coarse fraction, d_{coarse} = 1 mm. These values are similar to those reported for Wrightsville Beach (North Carolina), but we have also simulated the development of sorted bed forms for grain sizes (d_{fine} = 0.22 mm and d_{coarse} = 0.75 mm) observed over sorted bed forms at Tairua Beach (NZ). The current profile adopted is logarithmic in the vertical direction, and suspended sediment concentration decays exponentially from the bed. Unless otherwise stated, simulations presented here all begin with bed composition randomly changed at each cell with an average value of 30% coarse material. A horizontal domain of 100 $\times$ 100 cells is used for the simulations. The size of each cell is 5 $\times$ 5 m in the horizontal direction and 0.05 m in the vertical direction. Initial water depth is 20 m, wave period is 10 s, and amplitude of the initial bed perturbations is smaller than 0.01 m. External forcing conditions (wave height, mean current speed and direction) are allowed to change at each

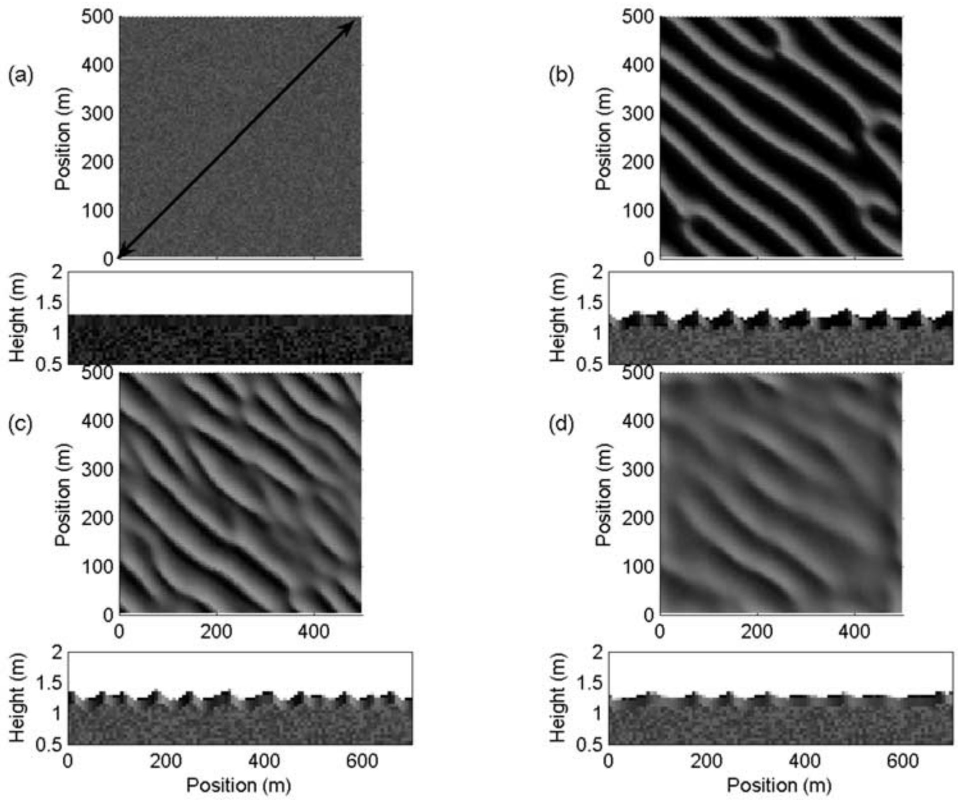


Figure 4. Effect of varying wave heights on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after 60 days of bed form evolution. Mean wave height is equal to 3 m, mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is composed of coarse (30%) and fine (70%) material. Standard deviation around the mean wave height is (a) initial configuration (the same for each of the following simulations), (b) $\sigma_H = 0.0$, (c) $\sigma_H = 0.1$, and (d) $\sigma_H = 0.8$. Mean current direction and position of the cross-sectional section is from the bottom left corner to the top right corner (shown by the arrow in Figure 4a).

iteration where one iteration corresponds to 24 hours. We have tested the model sensitivity when wave height is changed at each time step. The time step is equal to 100 s for all the simulations presented herein. Wave height will be selected from a Gaussian distribution of predefined mean and standard deviation, but similar results have been obtained using a Rayleigh distribution. The model has also been modified to allow for the possibility of constant net sediment aggradation or degradation at a predefined rate (expressed in m/yr). Fine or coarse sediment is introduced/removed by simply adding another term to the right-hand side of the discretized advection equation presented by *Coco et al.* [2007].

4. Results

4.1. Wave Height and Mean Current Variability

[12] The growth rate and final geometry of sorted bed forms vary with the characteristics of the wave forcing (Figures 3 and 4). In these simulations the wave height changes every time step roughly representing a polychromatic wavefield. Figure 3 shows how increasing values of the standard deviation of the wave height decrease the growth rate of the features, but does not completely prevent them from establishing. In terms of the overall pattern, Figure 4b shows how regular forcing contributes to the development of sorted bed forms characterized by a limited number of ‘defects’ (bifurcations or shapes that diverge from a regular configuration). For increasing values of the standard deviation (Figures 4c and 4d), more defects are present, different wavelengths appear to be superimposed without any of them completely dominating and, at some locations, no clear pattern is discernible. If simulations with increasing values of the standard deviation are run for longer durations (Figure 5), a steady state pattern of sorted bed forms is eventually established. For increasing values of the standard deviation, the spacing of the features tends to increase while the height decreases. This appears to indicate that waves larger than average play a more effective role in the shaping of the pattern geometry, given that larger waves produce larger plan view patterns but smaller bathymetric relief [*Coco et al.*, 2007].

[13] Increasing variability in the magnitude of the mean current while keeping the direction constant (apart from daily reversals) results in larger bed form heights and faster growth rates (Figure 6). This indicates currents faster than average are more important in shaping sorted bed forms. This is because faster currents tend to reduce the relative importance of morphodynamic diffusivity, which is related only to wave orbital velocity in the model.

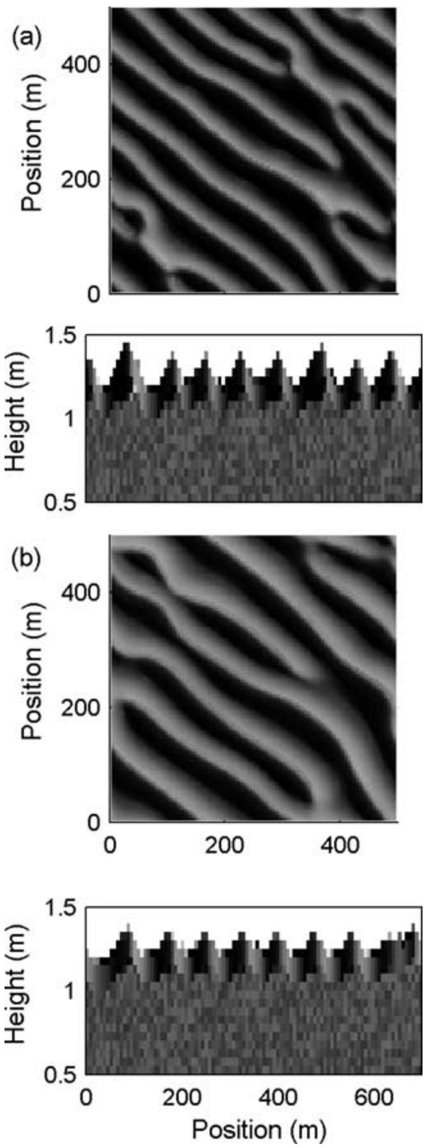


Figure 5. Effect of varying wave heights on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after 120 days of bed form evolution. Mean wave height is equal to 3 m, mean current is equal to 0.2 m/s (reversing daily), and initial water depth is equal to 20 m. Bed is composed of coarse (30%) and fine (70%) material. Standard deviation around the mean wave height is (a) σ_H = 0.1 and (b) σ_H = 0.8. Mean current direction and position of the cross-sectional section is from the bottom left corner to the top right corner.

[14] When current direction is kept constant (apart from daily reversals) but the magnitude varies, the emerging bed forms show little regularity (Figure 7a), but the crests appear to be oriented roughly perpendicular to the direction of the mean current. If the current direction is also allowed to change at each iteration (Figure 7b), although sediment sorting is still evident, the seabed patterns do not display the level of spatial organization typical of linear sorted bed forms. Furthermore, differences between consecutive iterations can be substantial (Figure 8) with large changes in spacing, amplitude, orientation, and regularity of the bed forms. Also, the cross sections presented in Figures 7 and 8 show the potential for the burial of coarse units.

[15] The overall implication is that, at sites where currents are stronger and/or the circulation is not limited to a single axis, sorted bed forms will be larger and less regular. To further demonstrate this idea we have run a simulation with the same current sequence as in Figure 7b but at a water depth of 30 m. As a result, sorted bed forms (Figure 9) require a longer time to form, develop a more regular configuration, and align to the direction of largest-magnitude current experienced during the simulation rather than to each forcing condition as in Figure 7b. These variable current results, together with Figures 3 and 4, point at the different role of waves and currents in the sediment transport parameterization and so in the development of sorted bed forms.

[16] Also, the dynamics associated with current variability might explain the differences between, for example, the North Carolina coast (characterized by a relatively narrow inner shelf, approximately straight shoreline, and uniaxial currents) where regular sorted bed form patterns are observed [*Murray and Thieler*, 2004] and locations like the inner [*Harrison et al.*, 2003; *Donahue et al.*, 2003] and outer (A. C. Hine, personal communication, 2006) SW Florida shelf (characterized by a wide shallow shelf, a nonrectilinear shoreline, and where current patterns are not restricted to a single axis) where less regular sorted bed form patterns are present. Similarly, these simulations might help explain the lack of regularity observed by *Ferrini and Flood* [2005] in shallow depths where it is possible that more complicated hydrodynamics might result in features characterized by limited rhythmicity.

[17] We also tested the development of sorted bed forms under a unidirectional, nonoscillating, current. Results show, in agreement with *Murray and Thieler* [2004], that no steady state is reached and the bed form spacing increases with time (Figure 10). Also in agreement with *Murray and Thieler* [2004], under oscillating currents with an asymmetry in the current duration, sorted bed forms increase in spacing at a slow rate and migrate in the dominant current direction (not shown). Finally, simulations with the mean current changing over an ellipse to represent environments where the mean current is primarily driven by tides still result in the development of sorted bed forms characterized by a height and spacing that increases with the largest current magnitude associated with the ellipse (not shown). The maximum current direction controls sorted bed form orientation.

4.2. Grain Size Variability

[18] Numerical simulations indicate a limited sensitivity when the variation in initial grain size distributions between cells is increased while keeping the average value for the whole domain fixed. This result indicates that the emergence of sorted bed forms does not depend on the details of the initial variability at smaller spatial scales. Increasing the initial variability between cells moderately slows the growth of the features but does not affect the final pattern. The dependency of the sorted bed form characteristics on average bed composition is reported in the companion paper [*Coco et al.*, 2007].

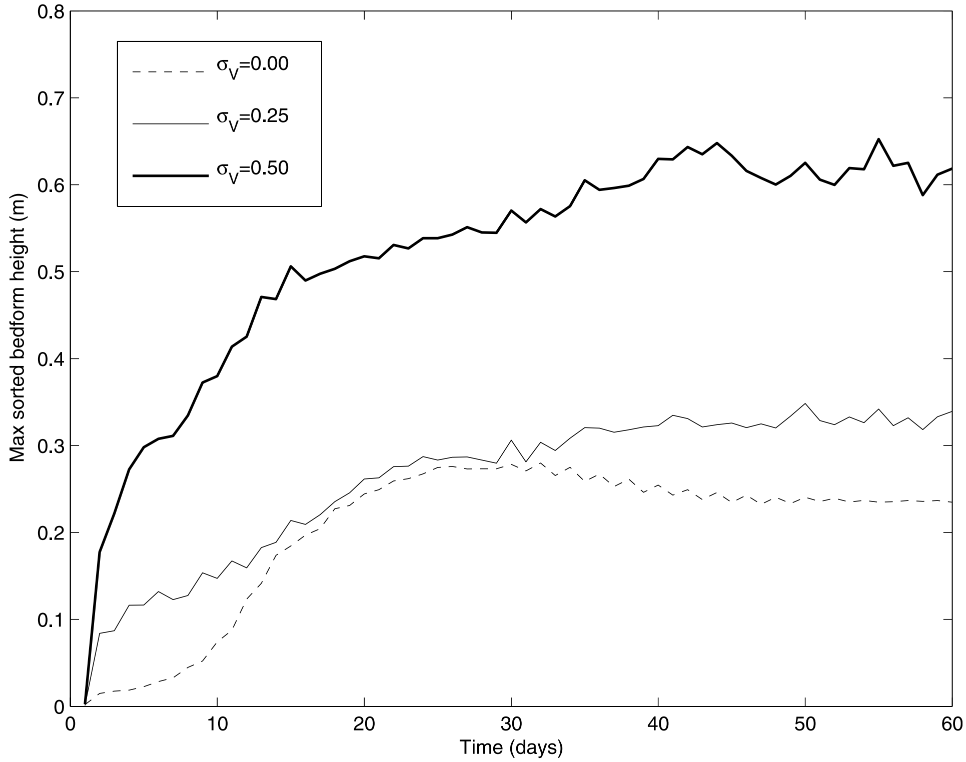


Figure 6. Growth rate of sorted bed forms over time. Wave height is equal to 3 m, and initial water depth is equal to 20 m. Mean current is equal to 0.2 m/s, while the values of σ_V in the legend indicate the standard deviation around the mean current speed in the Gaussian distribution. Sorted bed form height is evaluated as the difference between the maximum and minimum bed elevation over the whole domain.

[19] To address the variability that might be observed in a natural system, we have also run simulations with different parts of the domain characterized by different seabed compositions. As one might expect, sorted bed forms initially develop only where the bed is regionally characterized by mixed grain sizes (Figure 11a). However, sorted bed forms extend beyond the initial mixed grain size domain as advection by mean currents distributes the sediment (Figure 11b). As a consequence, sorted bed forms that are not very thick develop at locations where the substrate is not constituted by mixed grain sizes and where one, as a result, would not expect to see pattern development. This spreading occurs more rapidly under greater current speeds (Figure 11b). Although not a definitive test, this hypothesis provides a reasonable explanation for observations of sorted bed forms that are superimposed on a thick layer of fine sand (D. C. Twichell, personal communication, 2006).

[20] When mixed grain sizes exist everywhere, but with regionally (order of hundreds of meters or larger) different coarse-fine ratios, sorted bed forms still develop but display a striking lack of regularity. This is most likely related to interactions between emerging patterns with different length scales (Figure 11c). No data are currently available to test these simulations but, nevertheless, the possibility that variations in grain size can also affect the development of sorted bed forms including the shape and regularity of the pattern should not be discounted.

4.3. Net Aggradation/Degradation

[21] Several investigators (see *Murray and Thieler* [2004] for a review) have indicated that sorted bed forms tend to develop in sediment-starved environments. Other authors [*Green et al.*, 2004] have suggested that at least temporary burial of sorted bed forms can occur as a result of fine sediment deposition over the coarse domain especially in the case of a fast wave height decay after storm conditions. To investigate why sorted bed forms develop in some places and not in others, and how the coarse domains can be buried, we have simulated the development of sorted bed forms under conditions of net aggradation or degradation of fine sediment over a well-developed pattern.

[22] Simulations have been run with aggradation of fine beginning after sorted bed forms had already developed under wave height of 3 m imposed for only a few days (not shown). At the same time, to simulate the fast decay in wave height that might follow a storm, wave height was decreased from 3 to 1.5 m. The fine sediment deposition results in a pattern characterized by smaller height, smaller amount of coarse sediment present on the seabed surface, and loss of sorted bed form asymmetry (although in a later section it will be shown this is the result of the change in wave height rather than aggradation). These effects are enhanced if the same simulation is run for a larger water depth. Overall, sorted bed forms do not get buried unless extremely, and probably unrealistic, large values of aggradation are considered. Subsequent sorted bed form development, with aggradation switched off, leads to an increase

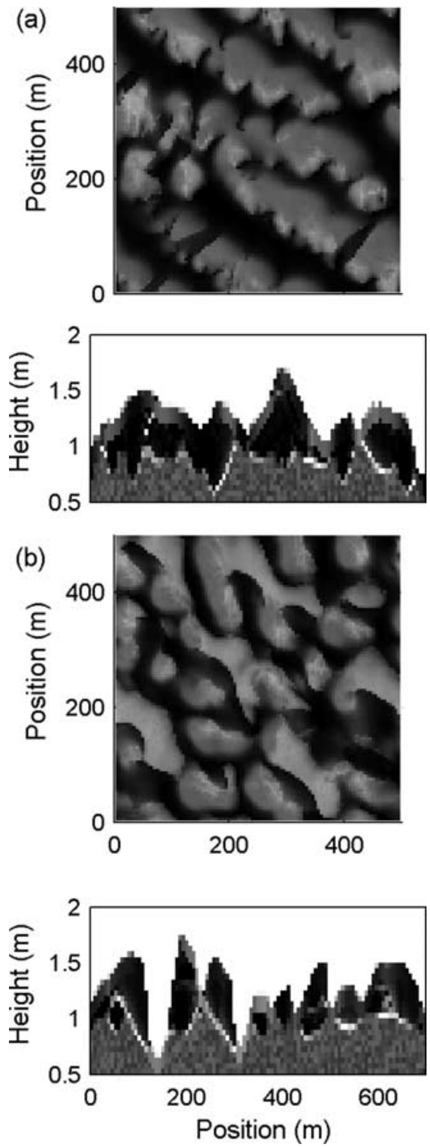


Figure 7. Effect of varying magnitude and direction of the mean current on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after 30 days of bed form evolution. Wave height is equal to 3 m, mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is composed of coarse (30%) and fine (70%) material. Standard deviation around the mean current is $\sigma_V = 0.30$. (a) Only current magnitude is changed at every iteration; mean current direction is from the bottom left corner to the top right corner. (b) Current magnitude and direction are changed at every iteration, and there is no preferred current direction. Cross-sectional section is from the bottom left corner to the top right corner.

in bed form height and a tendency toward the development of a larger spacing (not shown).

[23] We have also tested for the development of sorted bed forms under increasing fine sediment aggradation rate and no decay in wave height as would occur in the aftermath of a storm. The development of sorted bed forms is hampered only under high aggradation rates, indicating that sorted bed forms are not likely to develop in deltaic environments with large sediment supply.

[24] Simulations have been run with constant net erosion of sediment. Results indicate that, for large values of net erosion of the fine sediment (not shown), the pattern that develops has a complicated structure with the coarse grain size present over the majority of the surface and no clear

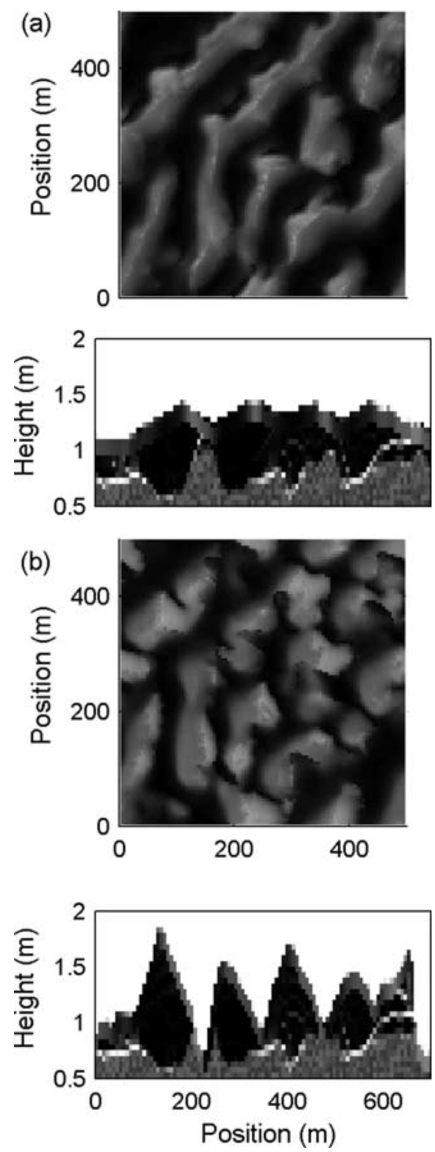


Figure 8. Effect of varying magnitude and direction of the mean current on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after (a) 29 and (b) 30 days of bed form evolution. Wave height is equal to 3 m, mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is composed of coarse (30%) and fine (70%) material. Standard deviation around the mean current is σ_V = 0.40. Current magnitude and direction are changed at every iteration. Cross-sectional section is from the bottom left corner to the top right corner.

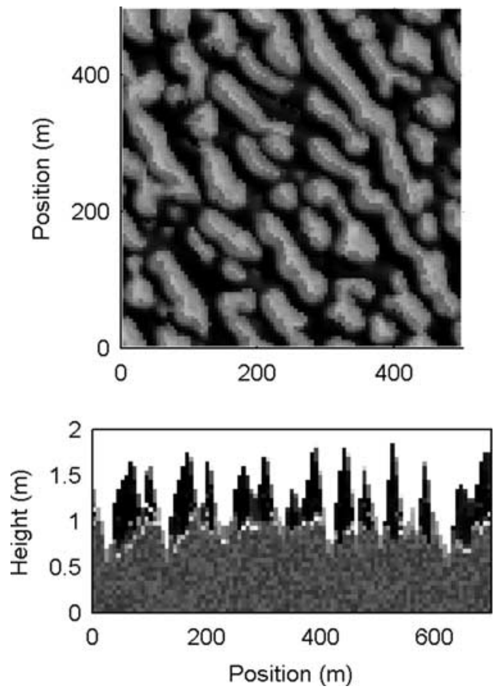


Figure 9. Effect of varying magnitude and direction of the mean current on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after 30 days of bed form evolution. Wave height is equal to 3 m, mean current is equal to 0.2 m/s, and initial water depth is equal to 30 m. Bed is composed of coarse (30%) and fine (70%) material. Standard deviation around the mean current is $\sigma_V = 0.30$. There is no preferred current direction (current magnitude and direction is changed at every iteration). Compare with Figure 7b. Cross-sectional section is from the bottom left corner to the top right corner.

spacing. Larger bed form spacings tend to emerge with time.

4.4. Systematic Variations in Wave Height

[25] Simulations have been run to assess the role of temporal changes in wave height. The first scenario analyzed (Figure 12) addressed the development of sorted bed forms under relatively small wave conditions (H = 2 m) and then, after a pattern had developed, under an increased wave height (H = 3 m). The results show that the pattern reorganizes under the larger waves into a configuration characterized by larger spacing and smaller bed form height. Notably, the new configuration (Figure 12b) displays a higher number of bifurcations and a larger bed form height than would have resulted by running simulations with H = 3 m for an equal amount of time starting with a planar bed (not shown).

[26] In an opposite experiment with high followed by low waves, the seabed responds differently depending on the difference between the initial and final wave height (Figure 13), and the different response is also related to the initial configuration of the sorted bed forms. The initial configuration (Figure 13a) considered for this experiment was the one resulting from large wave height (H = 5 m), which is characterized by large spacing and low relief. Subsequent forcing of H = 3 m resulted in a distinct reduction of sorted bed form spacing and increase in sorted bed form heights (Figure 13b). Starting from the H = 5 m configuration, forcing the system with lower wave heights (H = 2 m) did not affect the sorted bed form spacing, but it did affect the sorted bed form height (Figure 13c). Also, the shape of the developing features shows (compare Figures 13a and 13c) a more uniform segregation over the fine and coarse domains, with little upcurrent/downcurrent asymmetry. This type of feature has been reported by several authors

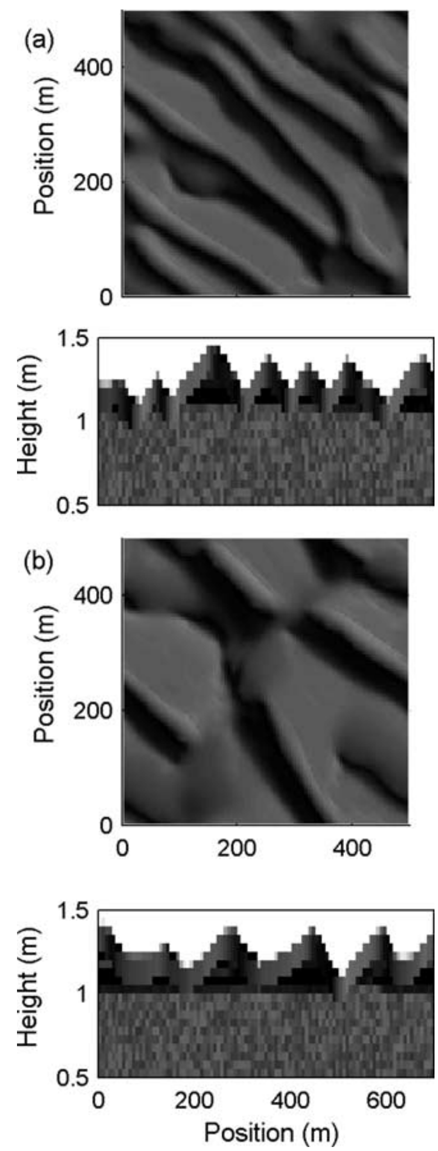


Figure 10. Development of sorted bed forms under a unidirectional current. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views after (a) 60 and (b) 120 days of bed form evolution under unidirectional (from the bottom left corner to the top right corner), nonoscillating current of 0.2 m/s. Wave height is equal to 3 m, and initial water depth is equal to 20 m. Bed is composed of coarse (30%) and fine (70%) material. Cross-sectional section is from the bottom left corner to the top right corner.

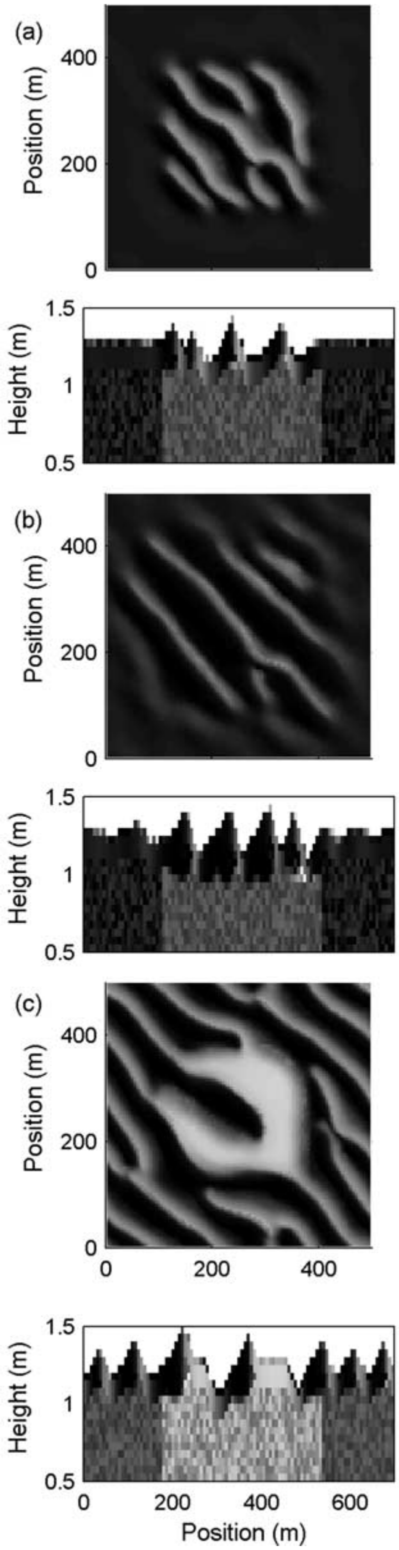


Figure 11. Effect of varying bed composition on the development of sorted bed forms: (a) 30% (5%) coarse material inner (outer) domain, (b) 30% (5%) coarse material inner (outer) domain but mean current magnitude is equal to 0.4 m/s, and (c) 60% (30%) coarse material inner (outer) domain. White (black) indicates coarse (fine) sediment.

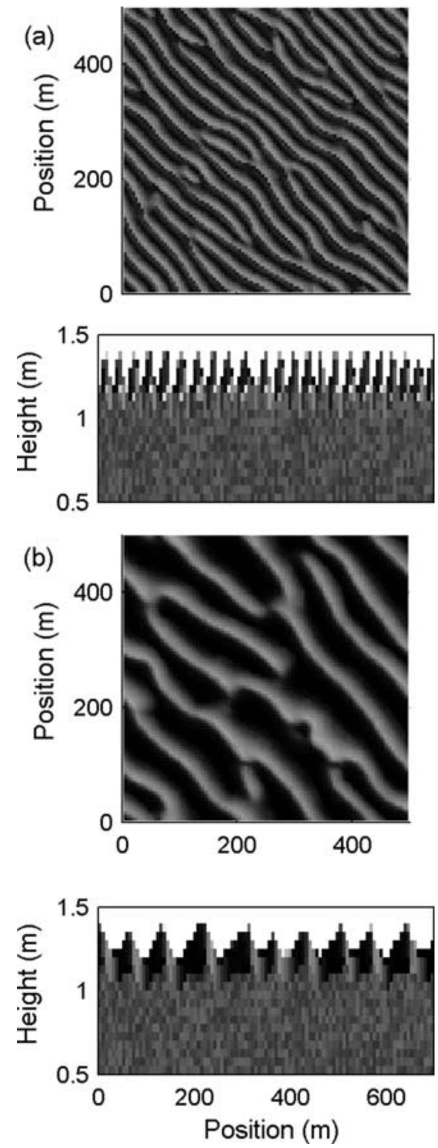
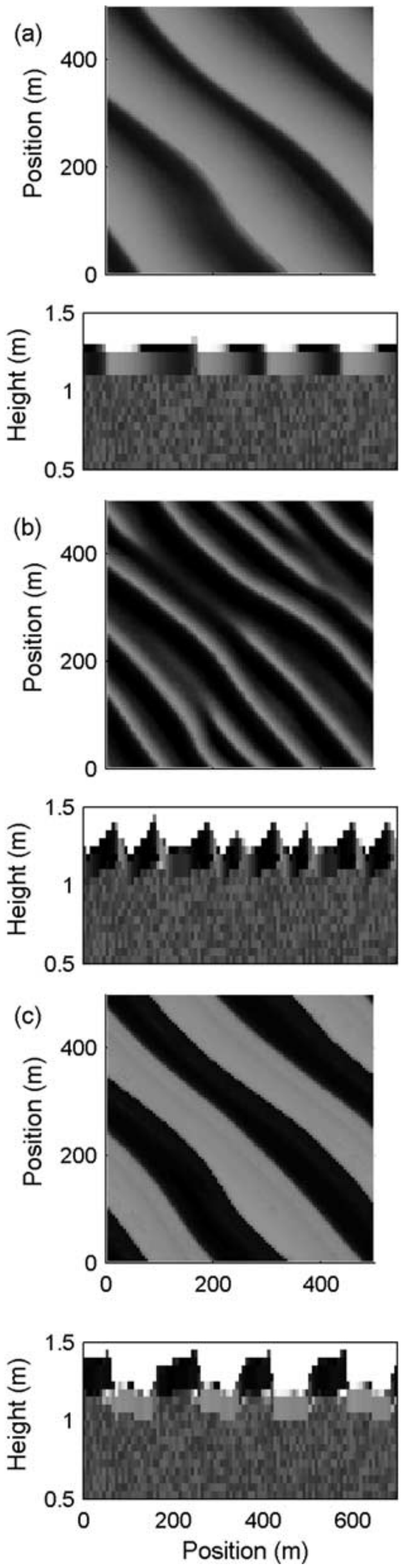


Figure 12. Effect of changes in wave height on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views. Mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is initially composed of coarse (30%) and fine (70%) material. Mean current direction and position of the cross-sectional section are from the bottom left corner to the top right corner. Simulation has been run for (a) 30 days with H = 2 m, followed by (b) 30 days with H = 3 m.

[*Cacchione et al.*, 1984; *Hume et al.*, 2003; *Goff et al.*, 2005]. The simulations suggest that such features do not represent a different type of bed form. Instead, they result from a particular sequence of hydrodynamic conditions reworking the seabed.

[27] A simulation was run with constant wave height (H = 2.5 m) apart from 2 days of higher waves (H = 5 m) in order to represent the effect of an isolated storm. Figure 14a shows the initial sorted bed form configuration developing under the low waves, which is nearly obliterated by the

storm, although some signatures of the pattern remain (Figure 14b). In particular, vertical segregation of material persists, with more coarse material on the surface than the average initial bed composition, and sorted bed forms have a larger wavelength than the prestorm pattern, which has implications for the reestablishment of sorted bed forms after the storm. The sorted bed forms that redevelop once wave height has been brought back to its initial value (H = 2.5 m) exhibit a slightly larger wavelength (Figure 14c) than did the original pattern (Figure 14a). A further increase in wave height (H = 6 m) causes sorted bed forms to disappear in just one day. This happens because wave-generated ripples, under this type of wave condition, do not develop at all and the large amount of sediment in suspension overcomes any differential sediment transport caused by the preexisting, large-scale, sorted bed forms. The same simulation has been run assuming a larger water depth over the initial, already developed, sorted bed form pattern. In this case, sorted bed forms tend to be maintained although their relief slowly decreases. This happens because even if wave-generated ripples do not develop, given the larger water depth, less sediment goes in suspension. Also, the larger wave height implies stronger diffusion of the sorted bed form features.



5. Discussion and Conclusions

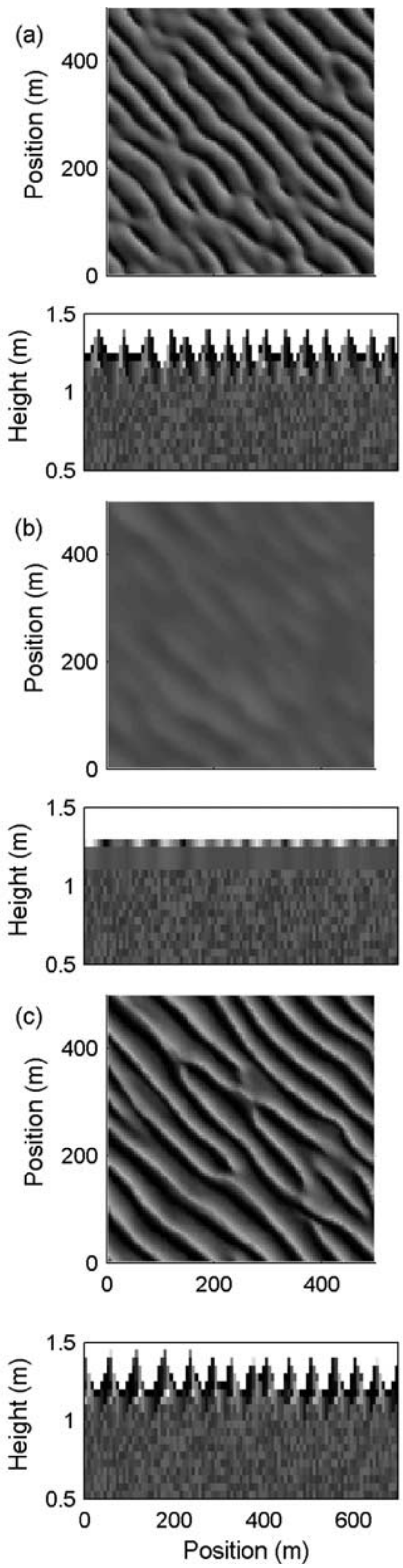
[28] We have simulated sorted bed form development under a variety of conditions to investigate the type of bed forms that can emerge as a result of variability in hydrodynamic forcing and/or in the grain size composition of the seabed.

[29] Results indicate that increasing variability in wave height reduces the growth rate of sorted bed forms, although a fairly regular spacing still emerges as observed, for example, by *Murray and Thieler* [2004] on the inner continental shelf off Wrightsville Beach (North Carolina). On the other hand, an increase in the magnitude and directional spreading of the current causes development of features that differ substantially from regular patterns of sorted bed forms. Specifically, the patterns that result are not necessarily organized into a regular spacing as observed in many field settings (see Table 1).

[30] Simulations that incorporate variation in wave height that might be associated with the rapid onset and decay of a storm display complicated results, with the final seabed configuration strongly depending on previous seabed configurations and forcing conditions. Nevertheless, these simulations indicate that large storms can destroy wave-generated ripples and so result in the disappearance of sorted bed forms. This type of simulation agrees well with field observations [*Hume et al.*, 2003; *Ferrini and Flood*, 2005] indicating the ephemeral nature of sorted bed forms in shallower areas where the effect of storms would be stronger. During storms in nature, the wave period as well as

Figure 13. Effect of changes in wave height on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views. Mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is initially composed of coarse (30%) and fine (70%) material. Mean current direction and position of the cross-sectional section are from the bottom left corner to the top right corner. Simulation has been run for (a) 30 days with H = 5 m, followed by (b) 30 days with H = 3 m or (c) 30 days with H = 2 m.

height changes. Longer-period storm waves will tend to rearrange the bed configuration more rapidly than in these simulations. The complex results from these relatively simple simulations suggest that model behaviors driven by forcing changes based on observed storms could be compared to prestorm and poststorm bed observations. Such an effort is under way.



[31] Spatial variability in grain size distribution is also likely to play a role in the overall development of sorted bed forms. For example, results indicate that, depending on the mean current magnitude, shapes resembling sorted bed forms could develop beyond the domain of mixed grain sizes, where sorted bed forms would not normally be expected to occur. Spatial variability in regional bed composition can also produce less regular patterns, with larger coarse domains corresponding to initially coarser regions.

[32] Finally, simulations involving net aggradation show the potential for the burial of sorted bed forms (as observed in vibracores by, for example, *Garnaud et al.* [2005] and *Chin et al.* [1997]) although large rates of deposition of fine sediment are required. On the other hand, under eroding conditions (fine sediment removal), sorted bed forms appear to be less regular and, as expected, the coarse domains occupy larger parts of the seabed.

[33] Overall, the present, relatively simple, simulations illustrate how the development of sorted bed forms is affected by environmental variables and variability. These basic results also indicate that the different sorted bed form shapes and patterns observed in the field (Table 1) might not necessarily be related to diverse physical mechanisms. Instead, regional variations in sorted bed form appearance may result from variations in local hydrodynamic and/or sedimentary conditions.

[34] The results provide guidance on what field observations now need to be collected. Because the model shows that rather large variations in morphology can result from subtle variations in bed sediments and forcing, quite specific field observations are now needed to test the model predictions. In particular, surveys displaying the temporal evolution of sorted bed forms, coupled with an analysis of the currents (magnitude, direction, and variability) and waves (height, period and variability) appear to be critical for relating changes in the shape of sorted bed forms and migration rates to environmental forcing. Finally, to provide a satisfactory initial configuration for model runs, spatial coverage of sediment types and underlying geology appears to be necessary. To allow for this type of detailed field/model comparison, the model will need to be improved, in particular, to allow for significant cross-domain changes in bed elevations. This will in turn allow exploration of how sorted bed form geometry is affected by changes in water depth and the related varying role of waves and currents. Field observations and further model development will

Figure 14. Effect of changes in wave height on the development of sorted bed forms. White (black) indicates coarse (fine) sediment. Square (rectangular) plots show plan (cross-sectional) views. Mean current is equal to 0.2 m/s, and initial water depth is equal to 20 m. Bed is initially composed of coarse (30%) and fine (70%) material. Mean current direction and position of the cross-sectional section are from the bottom left corner to the top right corner. Simulation has been run for (a) 18 days with H = 2.5 m, followed by (b) 2 days with H = 5 m, followed by (c) 18 days with H = 2.5 m.

provide a test of the underlying physical principles that shape the development of sorted bed forms.

[35] **Acknowledgments.** G.C., M.O.G., and T.M.H. acknowledge funding from the (New Zealand) Foundation for Research, Science and Technology (contract C01X0401). Part of this work was done while A.B.M. was visiting NIWA supported by the ISAT Program (Royal Society of New Zealand). The National Science Foundation (OCE0452178) supported A.B.M. Thanks to Chris Sherwood, Dave Twichell, and Rich Signell for prereviewing this manuscript. Thanks to K. MacLeod and I. Macdonald for assistance in preparing the final document. One anonymous reviewer, M. Kleinhans, J. Goff, and the associate editor helped to improve the manuscript.

References

Aubrey, D. G., D. C. Twichell, and S. L. Pfirman (1982), Holocene sedimentation in the shallow nearshore zone off Nauset Inlet, Cape Cod, Massachusetts, *Mar. Geol.*, *47*, 243–259.

Black, K. P., and T. R. Healy (1988), Formation of ripple bands in a wave-convergence zone, *J. Sediment. Res.*, *58*, 195–207.

Cacchione, D. A., D. E. Drake, W. D. Grant, and G. B. Tate (1984), Rippled scour depressions on the inner continental shelf off central California, *J. Sediment. Petrol.*, *54*, 1280–1291.

Chin, J. L., H. A. Karl, and N. M. Maher (1997), Shallow subsurface geology of the continental shelf, Gulf of the Farallones, California, and its relationship to surficial seafloor characteristics, *Mar. Geol.*, *137*, 251–269.

Coco, G., A. B. Murray, and M. O. Green (2007), Sorted bedforms as self-organized patterns: 1. Model development, *J. Geophys. Res.*, *112*, F03015, doi:10.1029/2006JF000665.

Diesing, M., A. Kubicki, C. Winter, and K. Schwarzer (2006), Decadal stability of sorted bedforms, German Bight, southeastern North Sea, *Cont. Shelf Res.*, *26*, 902–916.

Donahue, B. T., A. C. Hine, S. Tebbens, S. D. Locker, and D. C. Twichell (2003), Late Holocene estuarine-inner shelf interactions; is there evidence of an estuarine retreat path for Tampa Bay, Florida?, *Mar. Geol.*, *200*, 219–241.

Eittreim, S. L., R. J. Anima, and A. J. Stevenson (2002), Seafloor geology of the Monterey Bay area continental shelf, *Mar. Geol.*, *181*, 3–34.

Ferrini, V. L., and R. D. Flood (2005), A comparison of rippled scour depressions identified with multibeam sonar: Evidence of sediment transport in inner shelf environments, *Cont. Shelf Res.*, *25*, 1979–1995.

Field, M. E., and P. S. Roy (1984), Offshore transport and sand-body formation: Evidence from a steep, high-energy shoreface, southeastern Australia, *J. Sediment. Petrol.*, *54*, 1292–1302.

Forbes, D. L., and R. Boyd (1986), Gravel ripples on the Inner Scotian Shelf, *J. Sediment. Petrol.*, *57*, 46–54.

Garnaud, S., P. Lesueur, and T. Garlan (2005), Origin of rippled scour depressions associated with cohesive sediments in a shoreface setting (eastern Bay of Seine, France, *Geo Mar. Lett.*, *25*, 34–42.

Goff, J. A., L. A. Mayer, P. Traykovski, I. Buynevich, R. Wilkens, R. Raymond, G. Glang, R. L. Evans, H. Olson, and C. Jenkins (2005), Detailed investigation of sorted bedforms, or "rippled scour depressions," within the Martha's Vineyard Coastal Observatory, Massachusetts, *Cont. Shelf Res.*, *25*, 461–484.

Green, M. O., C. E. Vincent, and A. C. Trembanis (2004), Suspension of coarse and fine sand on a wave-dominated shoreface, with implications for the development of rippled scour depressions, *Cont. Shelf Res.*, *24*, 317–335.

Gutierrez, B. T., G. Voulgaris, and E. R. Thieler (2005), Exploring the persistence of sorted bedforms on the inner-shelf of Wrightsville Beach, North Carolina, *Cont. Shelf Res.*, *25*, 65–90.

Harrison, S. E., S. D. Locker, A. C. Hine, D. F. N. J. H. Edwards, D. C. Twichell, and D. J. Mallinson (2003), Sediment-starved sand ridges on a mixed carbonate/siliciclastic inner shelf off west-central Florida, *Mar. Geol.*, *200*, 171–194.

Hequette, A., and P. R. Hill (1995), Response of the seabed to storm-generated combined flows on a sandy arctic shoreface, Canadian Beaufort Sea, *J. Sediment. Res., Sect. A*, *65*, 461–471.

Hume, T. M., J. W. Oldman, and K. P. Black (2000), Sediment facies and pathways of sand transport about a large deep water headland, Cape Rodney, New Zealand, *N. Z. J. Mar. Freshwater Res.*, *34*, 695–717.

Hume, T. M., A. C. Trembanis, A. Hill, R. Liefting, and S. Stephens (2003), Spatially variable, temporally stable, sedimentary facies on an energetic inner shelf, in [CD-ROM], edited by A. Press, Am. Soc. Civ. Eng., Reston, Va.

Hunter, R. E., D. R. Thor, and M. L. Swisher (1982), Depositional and erosional features of the inner shelf, northeastern Bering Sea, *Geol. Mijnbouw*, *61*, 49–62.

Hunter, R. E., J. R. Dingler, R. J. Anima, and B. M. Richmond (1988), Coarse-sediment bands on the inner shelf of southern Monterey Bay, California, *Mar. Geol.*, *80*, 81–98.

MacIntyre, I. G., and O. H. Pilkey (1969), Preliminary comments on linear sand-surface features, Onslow Bay, North Carolina continental shelf: Problems in making detailed sea-floor observations, *Mar. Sediments*, *5*, 26–29.

Molnia, B. F., W. C. Schwab, and W. A. Austin (1983), Map of potential geologic hazards on the North Aleutian Shelf (lease sale 92), Bering Sea, *U.S. Geol. Surv. Open File Rep.*, 83–247, 3 pp.

Morang, A., and R. L. McMaster (1980), Nearshore bedform patterns along Rhode Island from side-scan sonar surveys, *J. Sediment. Petrol.*, *50*, 831–840.

Murray, A. B., and E. R. Thieler (2004), A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions," *Cont. Shelf Res.*, *24*, 295–315.

Reimnitz, E., L. T. Toimil, F. P. Shepard, and M. Gutierrez-Estrada (1976), Possible rip current origin for bottom ripple zones to 30-m depth, *Geology*, *4*, 395–400.

Schwab, W. C., and B. F. Molnia (1987), Unusual bed forms on the North Aleutian Shelf, Bristol Bay, Alaska, *Geo Mar. Lett.*, *7*, 207–215.

Schwab, W. C., E. R. Thieler, J. R. Allen, D. S. Foster, D. S. Swift, and B. A. Denny (2000), Influence of inner-continental shelf geologic framework on the evolution and behavior of the barrier-island system between Fire Island Inlet and Shinnecock Inlet, *J. Coastal Res.*, *16*, 408–422.

Swift, D. J. P., and G. L. Freeland (1978), Current lineations and sand waves on the inner shelf, Middle Atlantic Bight of North America, *J. Sediment. Petrol.*, *48*, 1257–1266.

Thieler, E. R., A. L. Brill, W. J. Cleary, C. H. Hobbs III, and R. A. Gammisch (1995), Geology of the Wrightsville Beach, North Carolina shoreface: Implications for the concept of shoreface profile of equilibrium, *J. Sediment. Res.*, *126*, 271–287.

Thieler, E. R., P. T. Gayes, W. C. Schwab, and M. S. Harris (1999), Tracing sediment dispersal on nourished beaches: Two case studies, in *Coastal Sediments '99*, edited by A. Press, pp. 2118–2136, Am. Soc. Civ. Eng., Reston, Va.

Thieler, E. R., O. H. Pilkey, W. J. Cleary, and W. C. Schwab (2001), Modern sedimentation on the shoreface and inner continental shelf at Wrightsville Beach, North Carolina, USA, *J. Sediment. Res.*, *71*, 958–970.

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